NON-FATAL EJECTION VERTEBRAL FRACTURE AND ITS PREVENTION *

by

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Non-fatal ejection vertebral fracture has been a common injury in aviators since ejection seats came into use. (1) The injury is defined as any fracture of a vertebra due to the force of ejection itself, in an individual who survives the ejection and all subsequent hazards of his emergency escape.

While many individuals who were killed, drowned or died during ejection and its sequelae may have suffered vertebral fracture, it is improbable that many of them died as a result of the vertebral fracture alone.

EXTENT OF THE PROBLEM

Several studies of the nature and extent of the problem have been made. Jones et al showed that 21% of 165 U. S. Navy aviators suffered vertebral fracture using a gun-type ejection seat over a 4 1/4 year period 1958-1963. (2) Of these, six were retired on disability and one additional died. Fryer found a 19% incidence in 220 R.A.F. ejection using a similar seat. (3) Hirsch found a 25% incidence in 55 Swedish Air Force ejections using a different seat. (4). More recently, Shannon found that in the U.S.A.F. during CY 1967 and 1968, there were 390 noncombat ejections with 116 persons suffering major nonfatal injury. (5) Forty-one of the major injuries were fractures due to ejection force, and 97% of these were vertebral fractures. In the combat ejections, 89% of major injuries due to ejection force were vertebral fractures, and 80% of all vertebral fractures suffered were due to ejection force.

In all, 31% of noncombat and 25% of combat major injuries on ejection were non-fatal ejection vertebral fractures. In both cases the ejection vertebral fractures were the largest single category of major injury.

As Shannon points out, vertebral fractures and other injury on ejection has been the primary factor in the capture of a substantial number of United States aviators.

DISTRIBUTION OF FRACTURED VERTEBRAE

Table I presents the distribution of the vertebrae fractured in 78 aviators, representing 100% of those suffering ejection vertebral fracture in the U. S. Navy during the period 1 July 1959 through 30 June 1965. These data while previously unpublished have a considerable overlap with those of Jones. (2) The method of collection of these data is outlined. (6) Vertebral fracture was diagnosed only on the basis of x-ray, thus avoiding some of the diagnostic uncertainties mentioned by Crooks. (7)

The principle feature of interest is that the distribution is bimodal with equal distributions around T8 and around T12. This is most interesting in view of the studies reported by Charles, Shannon and Smiley. (8, 5, 9).

Charles examined the fractures due to crashes (not ejections) and made the statement that "...the majority of fractures were concentrated in the lower thoracic and upper lumbar region. This is of course the area where the spinal column has the least support and where compression fractures would logically be expected to occur". (8) Shannon's study of emergency ejection injuries in 1970 states, "As expected, the vertebrae most frequently involved were T12 and L1 which accounted for 23% and 22% respectively". (5) (Emphasis supplied) Smiley states "... the distribution are clustered in the area of spinal flexion". (9)

DISTRIBUTION OF VERTEBRAE FRACTURED

	#	%
C1	1	0.7
C2	2	1.4
C6	1	0.7
T2	1	0.7
T3	1	0.7
T4	5	3.6
T5	7	5.5
T6	7	5.5
T7	4	2.9
T8	20	14.4
T9	18	12.9
T10	11	7.9
T11	9	6.5
T12	21	15.1
L1	19	13.7
L2	6	4.3
L3	3	2.2
S1	1	0.7
Coccyx	2	1.4
TOTALS	139	100.8

TABLE I

* Opinions or conclusions contained in this report are those of the author and do not necessarily represent the views or endorsement of the U. S. Navy.

Table II presents the U. S. Navy distribution 1959-1965 broken down into single fractures and multiple fractures. It is interesting that 40 persons suffered single fractures, and an almost equal number suffered multiple fractures. Similar data are available for Swedish, Canadian and Greek Air Forces. (4,9,10)

TABLE II

	DISTRIBUTION OF SINGLE FRACTURED VERTEBRAE		DISTRIBUTION OF MULTIPLE FRACTURED VERTEBRAE	
	#	%	#	%
C1			1	1
C2	1	2.5	1	1
C6			1	1
T2			1	1
T3			1	1
T4	1	2.5	4	4
T5	2	5.0	5	5
T6	1	2.5	6	6
T7			4	4
T8	5	12.5	15	15
T9	6	15.0	12	12
T10	2	5.0	9	9
T11	1	2.5	8	8
T12	7	17.5	14	14
L1	8	20.0	11	11
L2	3	7.5	3	3
L3			3	3
S1	1	2.5		
Coccyx	2	5.0		
TOTAL	40	100.0	99	99
PERSONS	40		38	

Comparison of fractured vertebrae distribution must be made on the basis of the percentage distribution rather than the absolute number, for obvious reasons. Such a comparison is presented in Table III for U. S. Navy, and published data for Swedish, Canadian, R.A.F. and Greek Air Forces.

DISTRIBUTION OF TOTAL VERTEBRAE FRACTURED

	U.S.Navy		Swedish AF(1)		RCAF (2)		RAF (3)		Greek AF (4)	
	#	%	#	%	#	%	#	%	#	%
C1	1	0.7								
C2	2	1.4								
C6	1	0.7								
T2	1	0.7	1	3.1						
T3	1	0.7	2	6.2						
T4	5	3.6	2	6.2			1	1.2		
T5	7	5.5	5	15.6	1	1.8	2	2.5		
T6	7	5.5	5	15.6	1	1.8	5	6.2		
T7	4	2.9	2	6.2	3	5.4	4	5.0		
T8	20	14.4	2	6.2			6	7.5		
T9	18	12.9	1	3.1	2	3.6	7	8.8		
T10	11	7.9	1	3.1	3	5.4	10	12.5	1	8.3
T11	9	6.5	1	3.1	8	14.2	9	11.2	2	16.7
T12	21	15.1	3	9.4	14	25.0	18	22.5	3	25.0
L1	19	13.7	2	6.2	12	21.4	10	12.5	5	41.7
L2	6	4.3	3	9.4	5	8.9	2	2.5	1	8.3
L3	3	2.2	2	6.2	1	1.8	1	1.2		
S1	1	0.7			1	1.8				
Coccyx	2	1.4					4	5.0		
Other					(5)	8.9	(1)	1.2		
TOTAL	139	100.8	32	99.6	56	100.0	80	99.8	12	100.0
PERSONS	78		13		30		40		6	

1. Hirsch, C. and Nachemson, A., Aerospace Medicine 1963 (Ref. #4)
2. Smiley, J. R. Aerospace Medicine 1964 (Ref. #9)
3. Fryer, D. I., F.P.R.C. 1166, 1961 (Ref. #3)
4. Symeonides, Pan P., AGARD 1971 (Ref. #11)

TABLE III

The U. S. Navy ejection vertebral fracture distribution by aircraft type for FY 1959 - 1965 is presented in Table IV. From these data, it is now possible to discern that the distribution of fractured vertebrae is different for each aircraft/seat type. While this fact is well known, presentation of vertebral fracture data for an entire Air Force as given in Table III would appear less useful in determination of the causes of fracture than presentation by aircraft/seat type. Several investigators have come to this realization.

VERTEBRAE FRACTURED DURING EJECTION BY A/C TYPE

	F3		F4		F8		F9		F11		T2		A4		Misc. A/C		TOTAL	
	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
C1															1	5.9	1	.7
C2											1	20			1	5.9	2	1.4
C6							1	1.8									1	.7
T2							1	1.8									1	.7
T3							1	1.8									1	.7
T4	1	4.8					3	5.4	1	11							5	3.6
T5	2	9.6					4	7.3					1	14.7			7	5.0
T6							4	7.3	1	11			1	14.7	1	5.9	7	5.0
T7	1	4.8					2	3.6							1	5.9	4	2.9
T8	5	24.0			3	25.0	5	9.1	2	22			2	29.4	3	17.6	20	14.4
T9	6	28.8	1	7.6	3	25.0	5	9.1	1	11			2	29.4			18	13.0
T10	3	14.4	2	15.2	1	8.3	3	5.4	1	11					1	5.9	11	7.9
T11			1	7.6	2	16.7	3	5.4	1	11	1	20			1	5.9	9	6.5
T12	2	9.6	4	30.4	3	25.0	7	12.7	1	11	1	20			3	17.6	21	15.1
L1	1	4.8	3	22.8			9	16.4	1	11	1	20			4	23.5	19	13.7
L2							4	7.3			1	20			1	5.9	6	4.3
L3							3	5.4									3	2.2
Sacrum													1	14.7			1	1.4
Coccyx			2	15.2													2	.7
TOTAL	21	100.8	13	98.8	12	100	55	99.8	9	99	5	100	7	102.9	17	100	139	99.9

TABLE IV

EFFECTS OF MULTIPLE EJECTIONS

In examining <u>all</u> cases of U.S.A.F. pilots who have made multiple ejections, Smelsey found a total of 116 cases through 31 December 1968. (10) Of this number, six sustained vertebral fractures on their initial ejection. Of the six, only one sustained a vertebral fracture on any subsequent ejection, and the vertebra fractured on the second ejection was not the same. The result in this case was return to full flying duties.

There is a possible source of bias in these data when attempting to calculate rates, since persons suffering an initial vertebral fracture on ejection may have left the service due to disability and therefore not been exposed to a second ejection; or may have transferred into a unit flying a non-ejection-seat aircraft ; or may have voluntarily left flying for other reasons. Thus the population at risk for a second ejection has the possibility of being a selected sample.

Ewing found that of 69 Designated Naval Aviators (DNA s) who suffered ejection vertebral fracture on initial ejection, only one suffered a vertebral fracture on a subsequent ejection. (6) It also involved a different vertebra. The number of those individuals making a second ejection is unknown. The result of the first fracture in this case was return to full flying duties (Service Group I). The result of the second fracture was return to permanently limited flying duties (Service Group II). The source of bias noted previously applies equally to this latter study since the number of DNAs leaving the service and thus no longer at risk following an initial ejection vertebral fracture is not well defined.

There is, therefore, insufficient evidence to allow prediction of vertebral fracture probability in a second ejection, given an aviator who suffered a vertebral fracture on a previous ejection; nor is it possible to give a prognosis of the ultimate effect on the individual (or his flying career) of a second vertebral fracture due to a second ejection. However, in neither of the two reported cases did the previously injured vertebra suffer a second fracture, nor did either case become disabled as a result of either fracture.

COSTS OF EJECTION VERTEBRAL FRACTURE

The study by Jones et al in 1964 noted that six aviators were retired for disability as a result of their fractures, out of a total of 34 persons who suffered ejection vertebral fracture. (2) Ewing's study shows all U. S. Navy DNAs retired for disability, and arranged by military rank. (6) These data are presented as Table V for the period 1959 through 1965, which partially overlaps the data of Jones, et al.

COSTS DUE TO PERMANENT REMOVAL OF DESIGNATED NAVAL AVIATORS FROM SERVICE GROUP I, FOLLOWING EJECTION VERTEBRAL FRACTURE

Rank	Disability Retirement	Limited Flying Duties	Total
CAPT			
CDR			
LCDR	2	2	4
LT	4	2 *	6 *
LTJG	5	1	6
ENS			

* Including one bilateral leg amputation

TABLE V

The cause of disability in five cases was paraplegia; intractable back pain in an additional five cases, and L5-S1 herniated disc in one case. As noted in Table V, five additional DNAs were never returned to the unlimited flying duties which they were performing at time of injury. They were returned to limited flying duties but were lost to the Navy as Service Group I aviators.

It should be noted that 16% of all DNAs suffering ejection vertebral fracture in the period 1959-1965 were retired for disability. If those restored only to permanently limited flight duties are included the percentage rises to 23%. Fryer's statement that permanent disability is rare, is not true for the U. S. Navy. (3) Crooks' statement "... the clinical importance of these crash fractures is negligible in the long term view" does not appear to apply to the U. S. Navy experience either. (7) A possible source of bias always exists in that non-disabled aviators are easier to locate and examine for follow up studies.

Another cost of ejection vertebral fracture is time lost from flying in Service Group I by the injured aviators. The definition of lost days is contained in the Appendix. Table VI presents the data by rank for the 70 DNAs. (6) When an aviator is not available to fly his mission, someone else must do it for him. Obviously, such normal time-loss events as leave, official travel and other illnesses and injuries cause any group of aviators to be somewhat overmanned. The time lost due to ejection vertebral fractures simply makes this manning requirement (commonly called the "seat factor") larger. This costs money for training of replacement pilots.

MAN-DAYS LOST DUE TO EJECTION VERTEBRAL FRACTURES, BY RANK FY 1959-1965, DNAS ONLY

Rank	Hospitalization	Total Days Absent from SG I	Number Individual DNAs
CAPT	93	178	2
CDR	302	754	3
LCDR	880 *	2,788 *	10
LT	2,132	4,833	29 **
LTJG	2,077	4,635	23
ENS	229	424	3
TOTAL	5,713	13,612	70 ***

* These figures include only known data. Duration of hospitalization and absence from SG I, when unknown, were determined by averaging for the particular fracture for this series. If such data were included, LCDR hospitalization would be increased 49 days; LCDR absence would be increased 59 days and CAPT absence would be increased 125 days.

** No hospitalization or days absent from SG I included for the bilateral leg amputation case.

*** While only 69 individuals suffered injuries, one suffered injuries in two separate accidents and is therefore counted as two persons for this table.

TABLE VI

In this study, 70 aviators lost a total of over 37.3 man years from their cockpits. This loss of operational capability may be as important as the losses due to disability retirement. The permanent loss of 16 jet fighter pilots in addition to the loss of 37.3 man years of jet fighter pilot time is not an inexpensive matter.

PREVENTION OF FRACTURE

An hypothesis of the mechanics of causation of non-fatal ejection vertebral fracture has been presented elsewhere. (12) It is hypothesized that certain movements of the individual vertebral bodies under $+G_z$ impact acceleration cause the characteristic fracture. If these motions can be prevented, fractures could only occur at markedly higher levels.

In the previous study (6), only one posterior vertebral fracture occurred out of 79 cases. The remainder were anterior compression fractures. It would therefore appear that there may be a mechanism limiting posterior compression, while not limiting anterior compression of the vertebrae.

The posterior compression limiter (or spring limiter) is seen to be the articular facets of the vertebrae, held together by ligaments as demonstrated in Figure 1. The facets serve as a posterior hinge for adjacent vertebrae, as demonstrated in Figure 2, allowing the anterior lips of the vertebral body to touch, but preventing contact of the posterior lips.

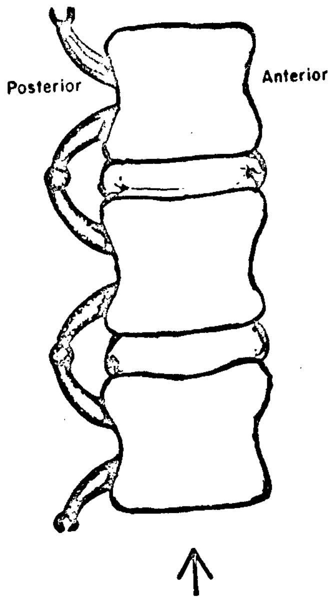

Fig. 1 Diagram of an erect spinal segment showing the relative postion of the articular facets and spinous processes.

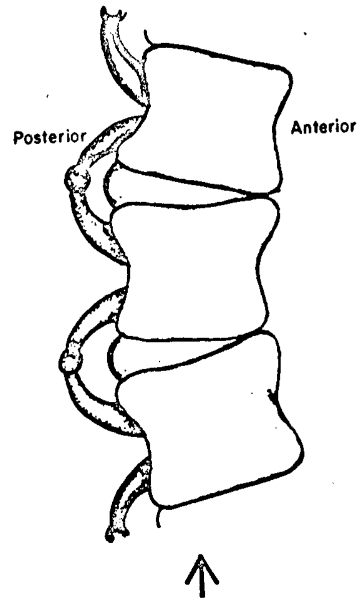

Fig.2 Diagram of a spinal segment showing relative positions of the vertebral bodies during flexion.

The hypothesis is therefore more specifically expressed: Posterior compression of the vertebral column in the thoraco-lumbar area is limited by the articular facets, while anterior compression is not.

If true, a means of preventing anterior compression fracture is suggested.

If the adjacent vertebrae could be forcibly restrained during $+G_Z$ impact acceleration in a position of relative hyperextension, as demonstrated in Figure 3, by compressing the posterior spinous processes, anterior compression would be limited. In such an event, it would be necessary to fracture the posterior spinous processes, or the articular facets or tear the ligaments (as shown in Figure 4) in order to cause an anterior compression fracture. The acceleration forces required to cause such fractures should be markedly higher than those necessary to cause anterior compression fractures as normally restrained. Thus, the vertebral fracture threshold should be markedly increased.

Experiments were performed using cadavers and a vertical accelerator to attempt to prove or disprove the hypothesis. (12, 13).

In these experiments, cadavers were restrained to a seat, on a vertical acceleration sled in three modes: erect, flexed, and extended (or "hyperextended"). Each cadaver served as his own control, and was x-rayed to rule out pre-run vertebral fracture. The cadaver was then accelerated to a low level in one of the three restrained modes selected at random. If no fracture occurred, the exposure was repeated in a different mode, and so on. When no fracture occurred at a particular peak $+G_Z$, the peak acceleration was increased by 4G and another series of three runs performed. Fracture, determined by x-ray, was the end point.

The "flexed" mode was obtained by using a tight lap belt with loose shoulder harness. The "erect" mode was obtained by using a tight lap belt and tight shoulder harness. The "extended" mode was identical to the erect mode except that a 2" x 4" wooden block was fixed between the posterior spinous process of L1 and the steel seat back.

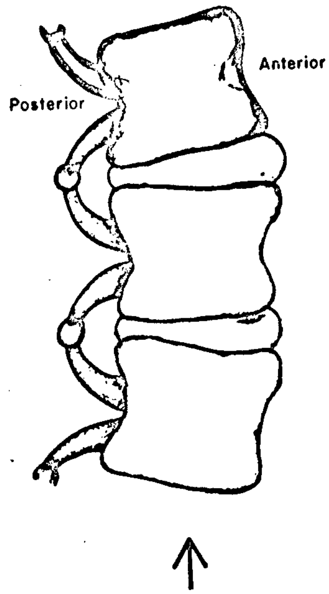

Fig. 3 Diagram of a spinal segment showing relative positions of the vertebral bodies during extension.

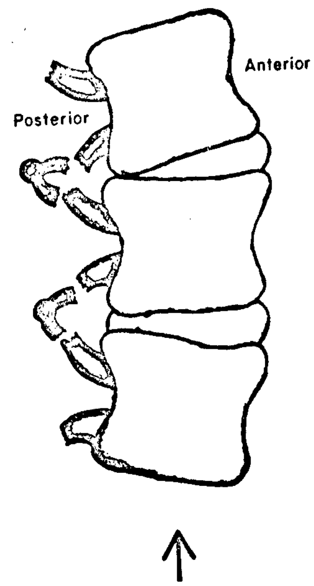

Fig. 4 Diagram of a spinal segment showing the mechanism required to permit posterior compression fractures of the vertebral bodies.

A summary of the results is contained in Table VII.

SUMMARY OF PEAK ACCELERATION VALUES
AT FRACTURE IN THE THREE SPINAL MODES

	Fracture level (g)	No. of Cadavers	Average age (yrs)
Extended	17.75 ± 5.55	4	61.5
Erect	10.4 ± 3.79	5	61.0
Flexed	9.0 ± 2.00	3	54.3

TABLE VII

Table VIII presents an analysis of variance that was possible despite the small sample size.

STUDENT'S t TEST OF FRACTURE g-LEVELS
BETWEEN THE SPINAL MODES

Modes	Sample size	t	P
Extended and erect	9	2.36	0.05
Extended and flexed	7	2.56	0.05
Erect and Flexed	8	0.58	>0.50

TABLE VIII

The differences in G level between the extended mode and the other two modes were found to be statistically significant ($P = 0.05$).

Comparison may be made of the fracture levels presented in Table VII with those presented by Ruff. (14) His work showed maximum tolerance of the individual vertebra in the T12 – L1 area in approximately the erect mode to be 24.5G and 23.0G respectively.

It is believed that the discrepancy can be resolved on the basis of age. Ruff's specimens were obtained at least in part from accident victims. It is presumed that those accident victims were youthful, whereas the average age of cadavers in the erect and extended modes of the present study was 61 years. The study by McElhaney and Roberts shows that strength of the vertebral body in the sixth decade of life is approximately half that in the second decade. (15) Empirical data from aircraft accidents indicate that the majority of individuals suffering ejection vertebral fracture are in their twenties.

If this relationship holds true, therefore, the average fracture level for the erect mode at age 20 would be roughly 20 G – 25 G and for the extended mode would be 35 G – 44 G. Since cadaveric bone is not as strong as living human bone or fresh cadaveric bone, the comparison becomes potentially even more meaningful.

CONCLUSIONS

It is considered that: (1) the hypothesis proposed has been supported by the data collected and presented; no data were observed to indicate that it was incorrect; and it is possible, for these particular data, to reject the null hypothesis at an acceptable level of statistical significance.

(2) Moderate forced hyperextension of the cadaveric vertebral column in the area of L1 by a 6" x 4" x 2 1/4" wooden block necessitates an increase of 50% in the peak sled acceleration level required to cause anterior compression fracture of the lumbar vertebrae over that required in the erect mode, and the difference is statistically significant.

(3) No posterior vertebral fractures resulted from any of these experiments.

(4) There is a preferred position, therefore, of the lumbar portion of the vertebral column during exposure to $+G_z$ acceleration from any source. This position can be achieved artificially by forcibly restraining the shoulder and pelvis of a cadaver to a rigid seat back and forcibly extending the lumbar vertebral column in the area of L1.

(5) This series of experiments, therefore, has considerable implications both for ejection-seat design and restraint-systems design for any human being subjected to $+G_z$ impact acceleration.

(6) It would appear from the evidence presented here that the internal structure of the vertebral column can be so arranged by restraint devices that it can withstand considerably greater loads without fracture than the same vertebral column not so restrained. This implies that the orientation of each vertebral body relative to those adjacent determines in part the sled peak-acceleration value in the $+G_z$ vector at which fracture occurs. Therefore, the characterization of the orientation of the entire vertebral column relative to the applied acceleration vector by a single direction is inadequate to explain the vertebral fracture threshold limits determined experimentally.

APPENDIX A

Definitions:

Service Group I – Aviators under 45 years of age who meet the physical standards for Service Group I. These aviators may be assigned to flight duties of an unlimited or unrestricted nature.

Service Group II – Aviators under 45 years of age who meet the physical standards for Service Group II, and aviators of Service Group I who temporarily meet only the physical standards for Service Group II. Aviators of Service Group II are restricted from carrier operations except in helicopter.

Service Group III – Aviators 45 years of age and over who meet the physical standards of Service Group I, II or III and those aviators under 45 years of age who (1) are recovering from illness or injury or (2) meet the standards of Service Group III but are not physically qualified for the other service groups when the needs of the service and individual's flying experience specifically justify their employment in such a limited status. Those aviators assigned because of temporary physical defects are retained in Service Group III for a period up to 6 months, at the end of which time they are re-examined for classification. Should the temporary disability warrant a longer period in order to fully recuperate, they can be retained in this group for additional six (6) month periods before final classification is effected.

DNA – A designated naval aviator.

NFO – A naval flight officer.

Hospitalization Day – One in which the individual was listed by the hospital as a patient.

Absent from Service Group I Day – One in which the individual was hospitalized, grounded, or in any other Service Group (II or III) as a result of an ejection vertebral fracture. These periods are terminated when an individual dies of his injuries, is placed either on the temporary or permanent disability retirement list, or returns to SG I.

Grounded Day – One in which an aviator is discharged from the hospital but has not yet recovered from his injuries sufficiently that he may be returned to flying duties in any service group.

Service Group III Day – One on or after that date on which the aviator is found physically fit by the Bureau of Medicine and Surgery to perform duty involving flying in Service Group III, and prior to being returned to either Service Group I or II.

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